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ABRL Monograph Series

No. 1

MICROMINIATURIZED ELECTRONICS
IN
BIOLOGY AND MEDICINE

American Biophysics Research Laboratory

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ABSTRACT

This report is prepared primarily for biologists and biophysicists actively engaged in the field of biotelemetry in order to acquaint them with microelectronics and its particular applications to their areas of interest. Biotelemetry is defined here as the transmission of information concerning biological parameters from a test specimen or organism to an observer. By the word transmission, we imply that the organism and observer are remotely located. Since we are primarily concerned with reaching an audience which is not actively engaged with electronic research, nor the advanced construction techniques utilized in microcircuitry, detailed technical analysis has been omitted, although the references cited will provide information of this nature. Our most important consideration is the application of microtechnology to biological problems.

First, a brief semi-technical description of the methods and techniques of microelectronics is presented. Transducers and power sources are then treated in turn. Finally, the latter portion of the paper is devoted to examples and applications of microminiaturized telemeters to specific biological problems. Also, the limitations of present microminiaturization techniques as applied to biotelemetry are discussed, and conclusions are provided about future biotelemeters and the directions which might be taken in their development.

PREFACE

The Office of Naval Research has recognized the necessity for a mutual appreciation and a more complete understanding of the problems which bridge the gap between the physical and life sciences. This recognition is the direct result of providing prior support in the investigation of new techniques in Biotelemetry.

This Technical Report has been prepared to aid the Biologist and Biophysicist in more clearly understanding his applicable problem areas, and thus enable him to prepare a more definitized expression of his requirements for electronic circuitry.

Special acknowledgment is given to Dr. S. R. Galler, Head of the Biology Branch of the Office of Naval Research, for his foresight and encouragement in the preparation of this report.

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SECTION I
MICROELECTRONICS

A. INTRODUCTION

Microelectronics has been defined in many ways. Perhaps the simplest and most exhaustive definition would be "the production and design of systems to perform electronic functions utilizing components several magnitudes smaller than that required by conventional techniques and components". Although this "definition" is extremely flexible, in fact, so flexible that it almost ceases to be a definition, it is the primary one which may properly be used to encompass the techniques being employed today. These statements gain much more significance if one attempts to trace the evolution of man's endeavor to compress electronics into smaller and smaller volumes.

An example of this evolution is the vacuum tube. The original vacuum tube triode of De Forest was approximately the size of the modern electric light bulb. A slight reduction in size occurred with the introduction of such tubes as numbers 81, 80, 78, etc. The advent of the octal type of tube, such as the modern 6L6, 6V6, etc., provided at least a 50% reduction in size. Another 50-75% reduction in tube size occurred with the miniature tubes such as the 6AG5, etc., and, in addition, multiple units (duo-diodes, dual triodes, diode triodes) were enclosed in a single glass envelope, such as the 12AU7, 12AT7, etc. An additional reduction in tube size resulted in the subminiature tubes introduced by such companies as Raytheon and Sylvania. This was accompanied by an approximate 50% decrease in volume. Thus, in the span of some 35 years the vacuum tube was reduced to less than 1/8 of its original volume and its reliability was greatly increased.

During the corresponding period of time, resistors, capacitors, and inductors underwent comparable size reductions.

Microelectronics may be said to have really begun with the development of the transistor at Bell Telephone Laboratories in 1948. The transistor is an active solid state device which can be utilized to perform many, if not all, of the functions of the vacuum tube. The basic advan-

tages over vacuum tubes are reduced size, reduced power consumption, ability to operate on low voltage power sources, and absence of radiated heat. An encased transistor has a maximum volume equal to approximately 1/10 that of a conventional miniature vacuum tube and, at most, 1/5 that of the subminiature tubes. An unencased transistor is even smaller, occupying a volume less than 1/100 that of a subminiature tube. Table A-1, Appendix A, presents the representative size of active components.

By utilizing materials of higher resistivity and space-saving construction techniques, resistor sizes were reduced. Since transistors are low power devices, it is possible to use resistors having a power rating of 1/4 or 1/8 of a watt and in some cases even 1/20 of a watt. The capability of a resistor to dissipate heat is directly related to its surface area, and thus, at these low power ratings, it became possible to use miniaturized resistors. Capacitors were reduced in size by using more effective dielectrics and thinner foils.

The gradual development of vacuum-deposition techniques, in which thin layers of materials are laid down on inert substrates such as glass or ceramics, permitted the production of thin-film resistors and capacitors. Eventually these techniques became the working tool of micro-circuit development. Multiple resistors and capacitors could be placed on a single substrate and connected together with conducting films. Any combination of passive networks may be assembled by this method. The addition of a transistor or transistors to the passive network results in what is called an active circuit. This is only one form of a circuit to which the term microminiaturized may be applied. This point will be considerably amplified in the following sections.

Although inductors have been considerably reduced in size by the use of more efficient core materials, microminiaturization has only been achieved for very small values of inductance by using thin-film deposition techniques. We shall now consider the various approaches in additional detail and point out the advantages and disadvantages of each.

B. APPROACHES TO MICROMINIATURIZATION

Presently, four distinct approaches to microelectronics can be distinguished. They are: (1) reduction in size of conventional components with more economical packaging techniques; (2) two-dimensional thin-films; (3) three-dimensional solid state devices; and, (4) molecular electronics.

1. Size Reduction of Conventional Components

The work on this approach to microminiaturization began in 1958 with a contract to RCA from the United States Army Signal Corps. RCA in turn subcontracted to various manufacturers of capacitors, resistors, etc., for the production of miniaturized versions of their products.

This approach is called the "Micromodule" technique and the individual components which are joined together to form a functioning micromodule are called microelements. Each microelement is placed on a wafer 0.3 by 0.3 inch square and 0.010 to 0.030 inch thick providing sufficient area to allow the realization of most conventional component values. These elements are placed one on top of the other and interconnections are made by means of riser wires running from top to bottom lying in notches around the perimeters of the individual wafers. Parts densities on the order of several hundreds per cubic inch are possible.

Advantages:

a. Presently available for utilization.

b. Facilitates physical layout of equipment due to uniform packaging.

c. Low cost production in larger quantities.

d. Reliability.

Disadvantages:

a. Limited to "square" form factor.

b. Relatively costly in small quantities.

c. Size reduction not as great as that obtainable by other techniques.

Two additional techniques developed through this approach are; (1), the "Cordwood" technique, which utilizes miniature components placed together and connected across the ends or to thin wiring wafers; and (2), the "Swiss-cheese" technique, which utilizes miniature components inserted

in holes in a printed circuit board or a substrate.

2. Two-Dimensional Thin-Films

Several manufacturers actively engaged in component research, utilize ceramic substrates which have printed connections and printed resistors. Capacitors and transistors are soldered into the circuit. The entire assembly is then hermetically sealed into a small can with leadout wires. A parts density of 200-300 parts per cubic inch is attainable.

Advantages:

a. Presently available on a custom basis.

b. Parts fabricated at a single location.

Disadvantages:

a. Utilizes only carbon resistors.

b. Does not provide for the interconnection of many stages.

c. Quite costly in small quantities.

Diamond Ordnance Fuze Laboratories, a government agency doing research for the Department of the Army, uses a similar technique. Resistors and wiring are printed, but by using wafer capacitors and uncased transistors, parts densities of 2000 per cubic inch become possible.

Advantages:

a. No soldered joints.

b. Excellent configuration for interconnections.

Thin film techniques can be used advantageously in place of printed wiring and resistors. Capacitors can also be laid down directly on the substrate. Parts densities should be several thousand per cubic inch.

Advantages:

a. Circuits having greater stability.

b. Finer line widths.

Disadvantages:

a. May be impossible to adjust resistances inexpensively.

b. May be less economical due to variety of materials to be deposited.

3. Solid Circuit Technique

This technique utilizes a semiconductor substrate a few mils thick

upon which thin conducting films are applied. Various portions of the semiconductor serve as resistors and capacitors. By depositing other semiconductor materials on the substrate, or using diffusion techniques, transistors and diodes may be built. This small piece of semiconductor, when connected to the proper operating voltages, then functions as a complete circuit. Parts densities of 10,000 per cubic inch are possible.

<u>Advantages</u>:

a. Very high parts density.

b. Inexpensive production costs.

c. Improved reliability.

<u>Disadvantages</u>:

a. Temperature dependence of most semiconductors.

b. Yields may be low.

c. Lead-out configurations may be limited.

4. <u>Molecular Electronics</u>

Multiple-junction semiconductors exhibit phenomena which are unique and unexplained. These can be used to perform the same functions as conventional components used in ordinary circuits. Hence, functional circuits can be built utilizing these special properties. Parts densities of 10,000 per cubic inch may be expected.

<u>Advantages</u>:

a. Circuit simplification.

b. Improved reliability.

<u>Disadvantages</u>:

a. Insufficient knowledge of phenomena involved.

b. Lack of control of thermal characteristics.

c. Placement of leads may be difficult.

Table A-II in Appendix A presents a summary of some of the companies interested in the techniques described in this paragraph.

Figures 1 through 6 illustrate some of the processes employed in the solid-circuit approach to microminiaturization. This technique as applied

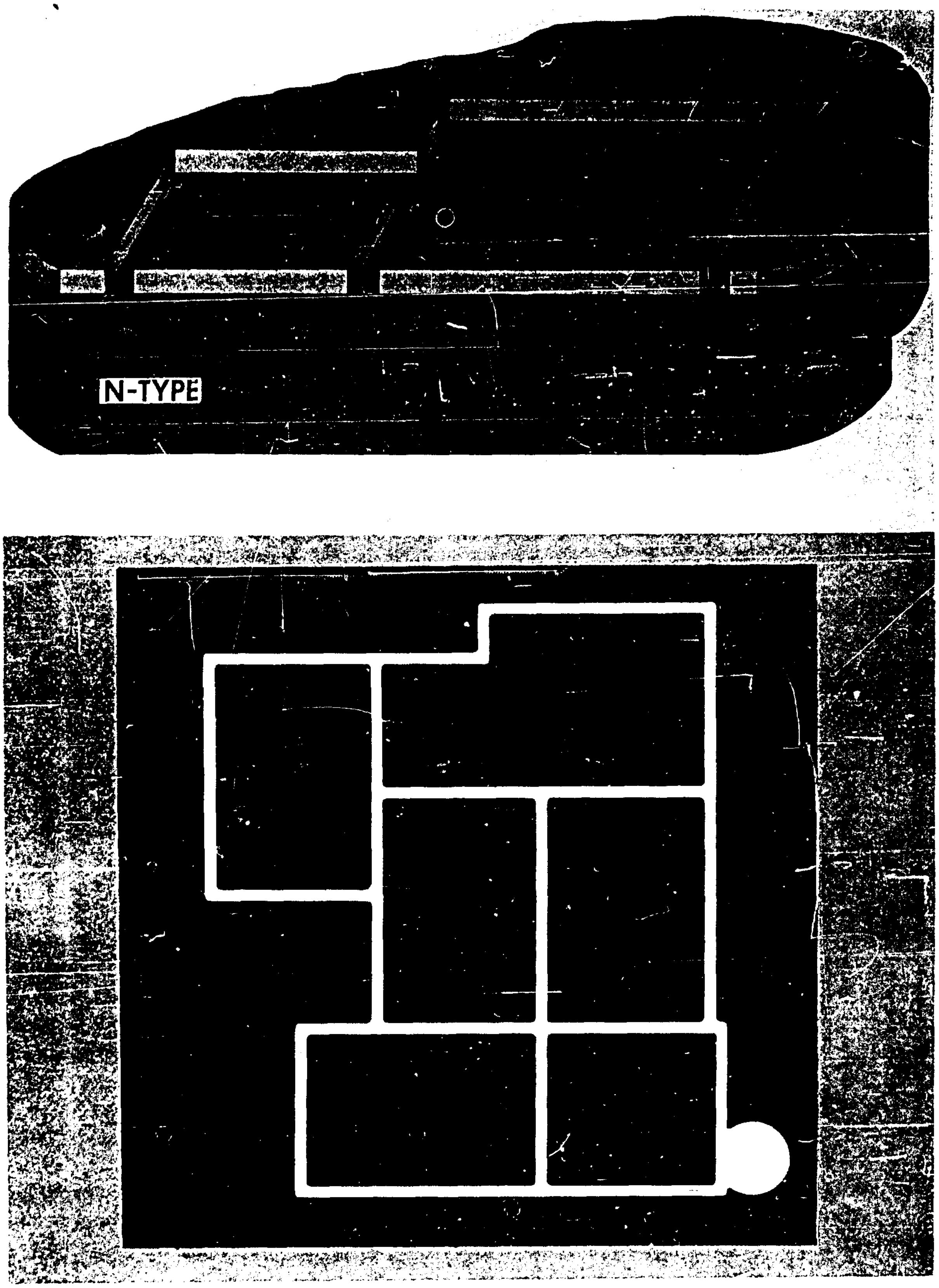


Figure 1. Isolation Masking

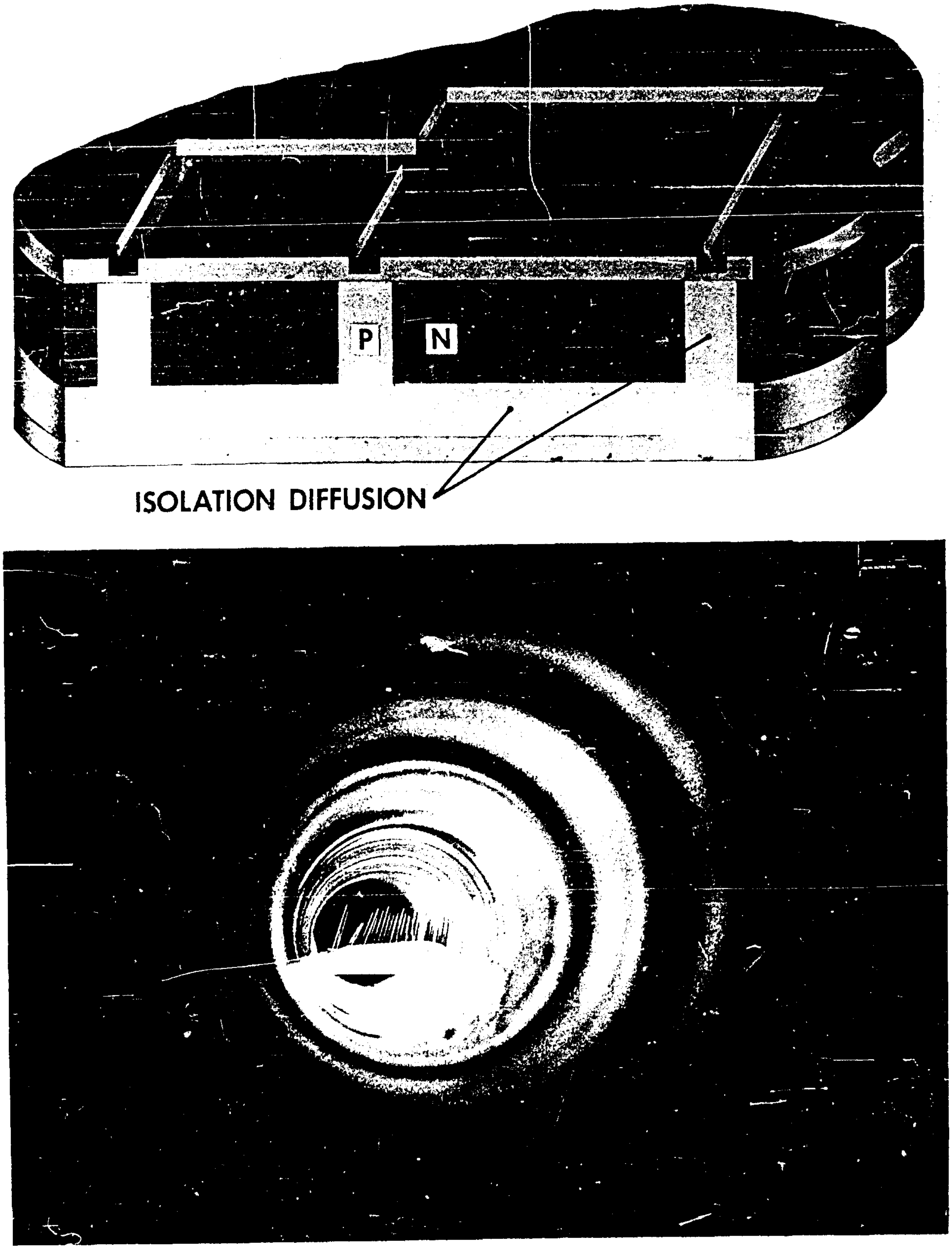


Figure 2. Isolation Diffusion

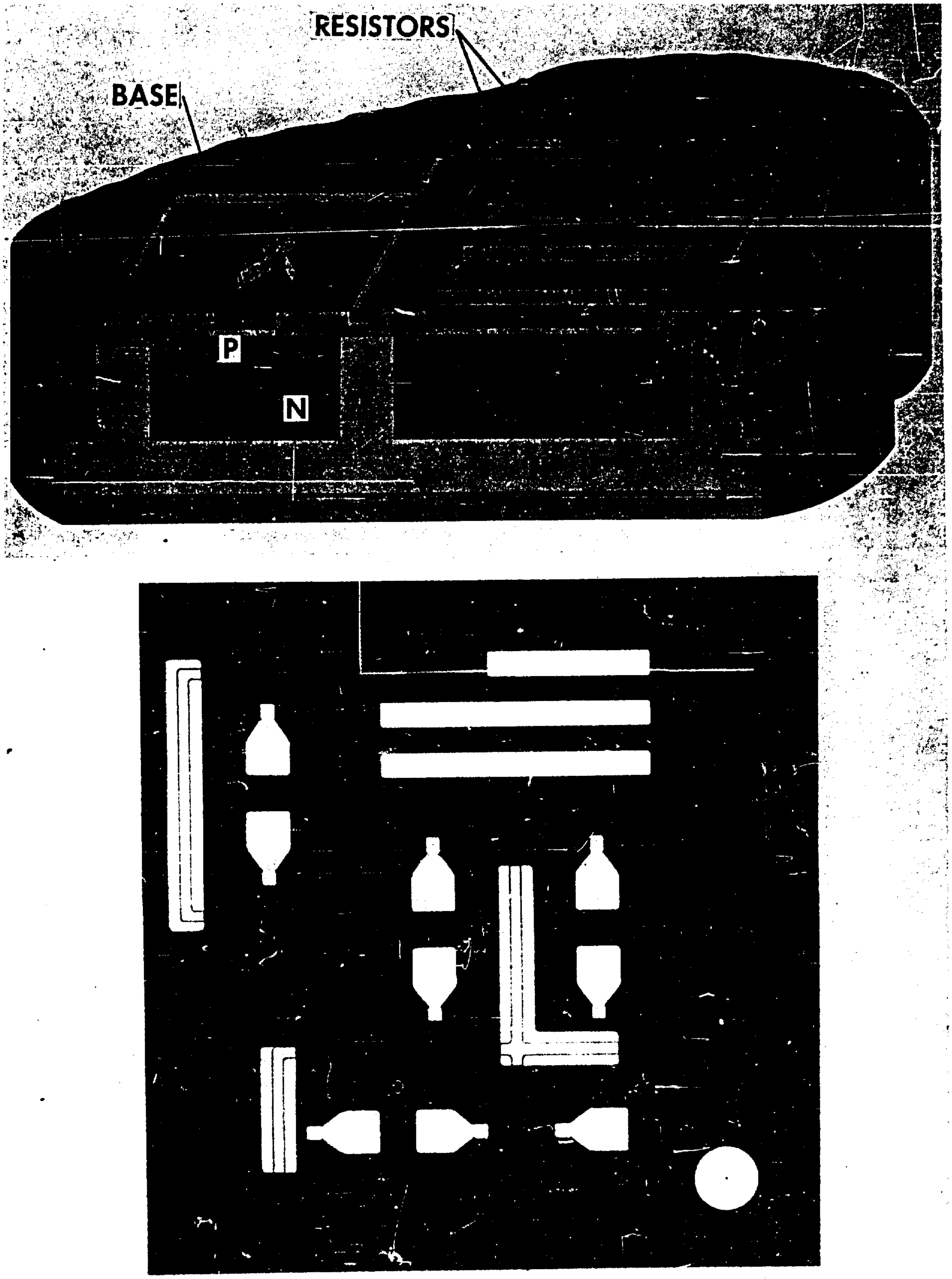


Figure 3. Masking and Base Diffusion

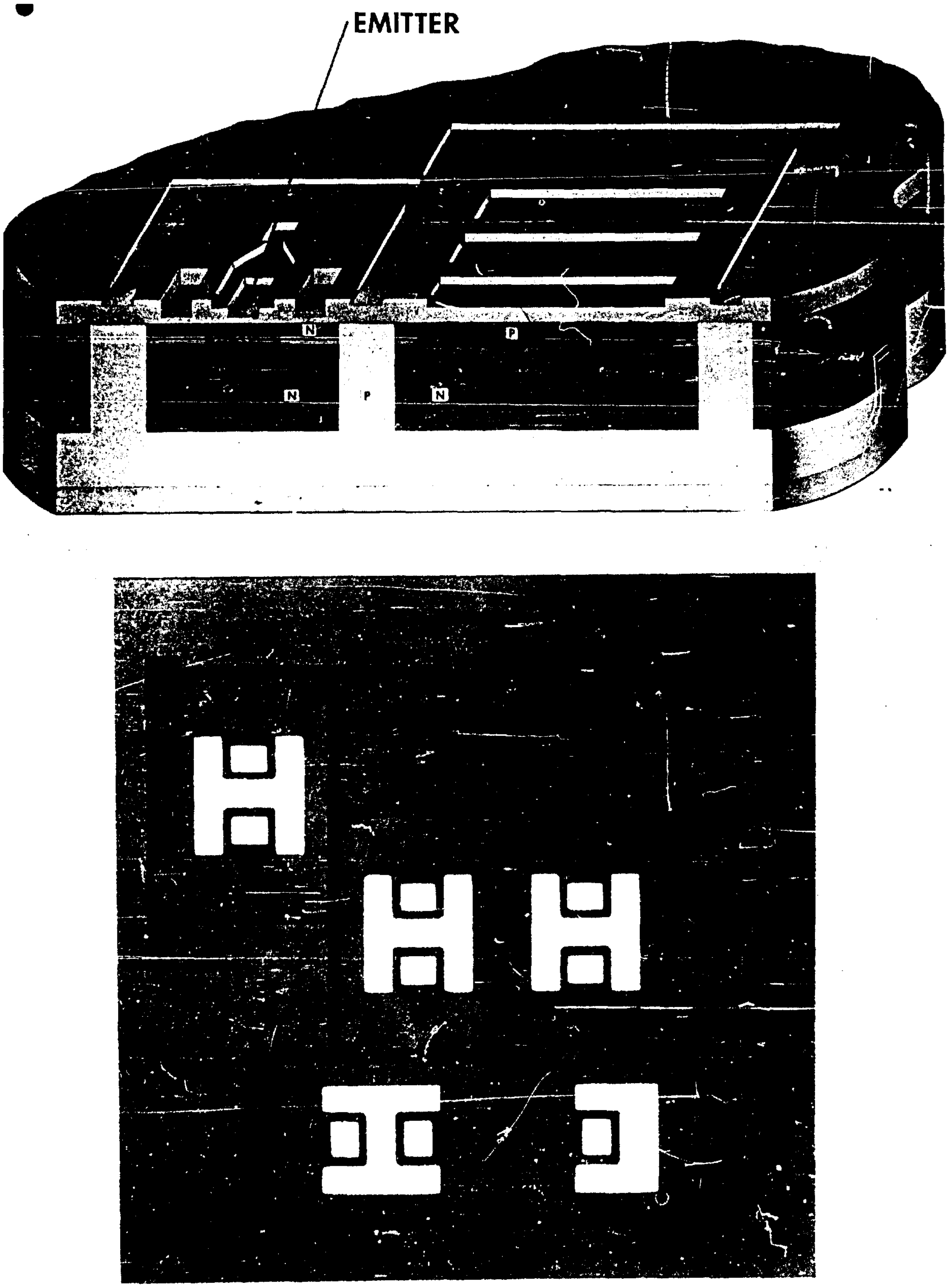


Figure 4. Emmitter Masking and Diffusion

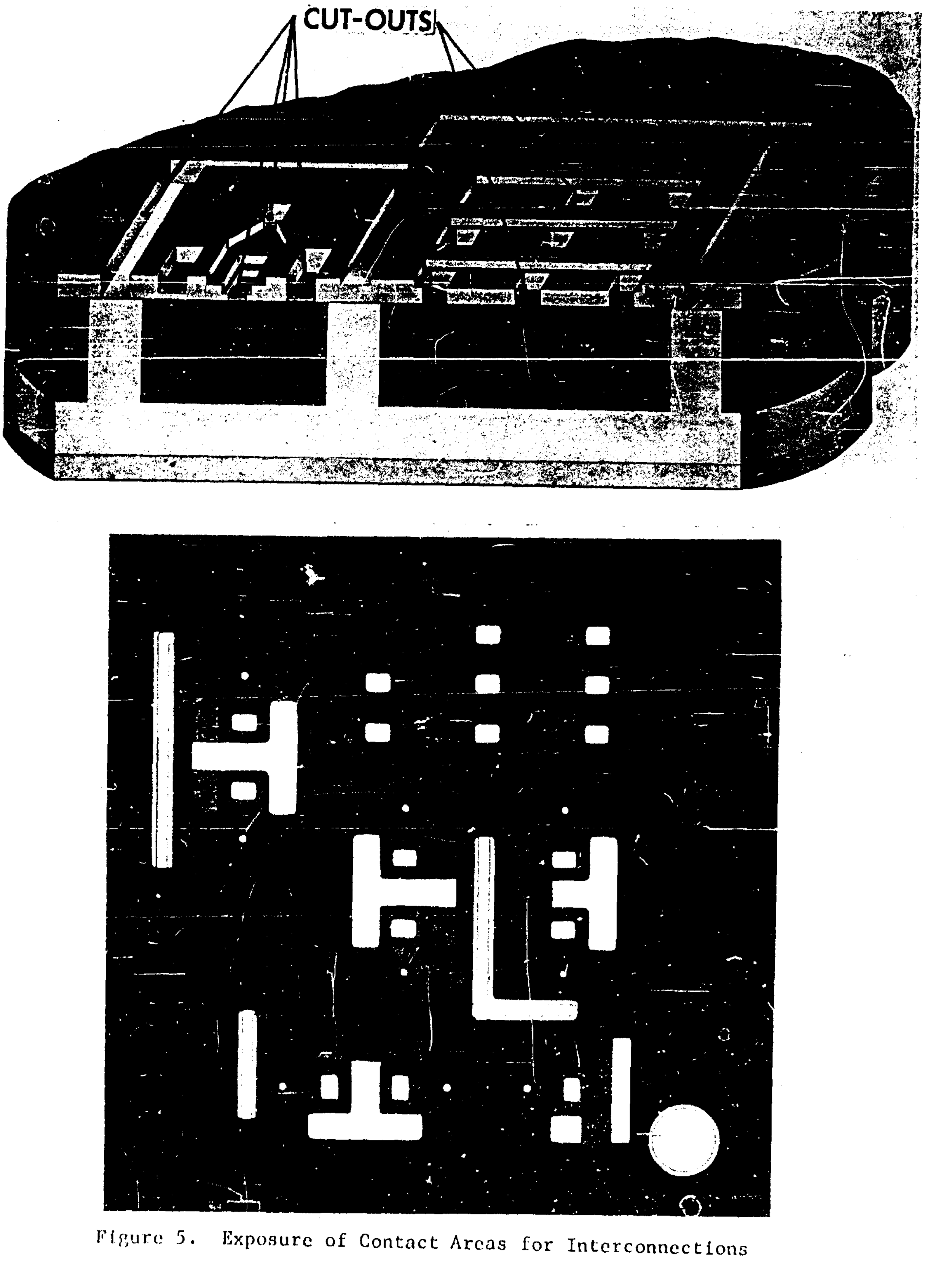
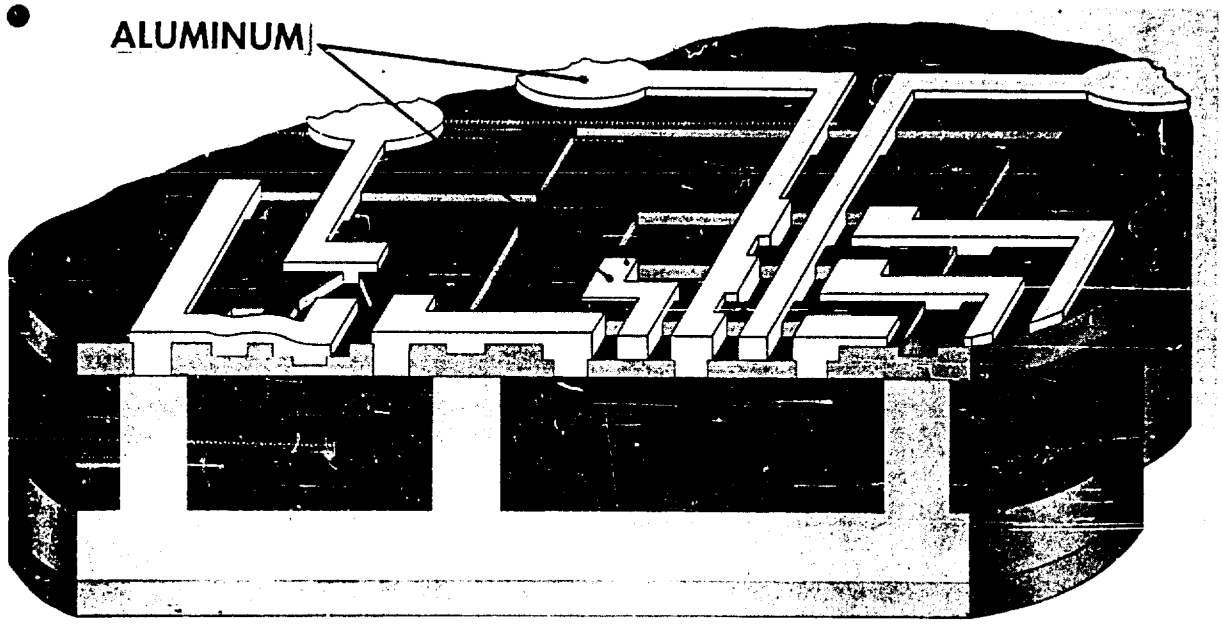


Figure 5. Exposure of Contact Areas for Interconnections



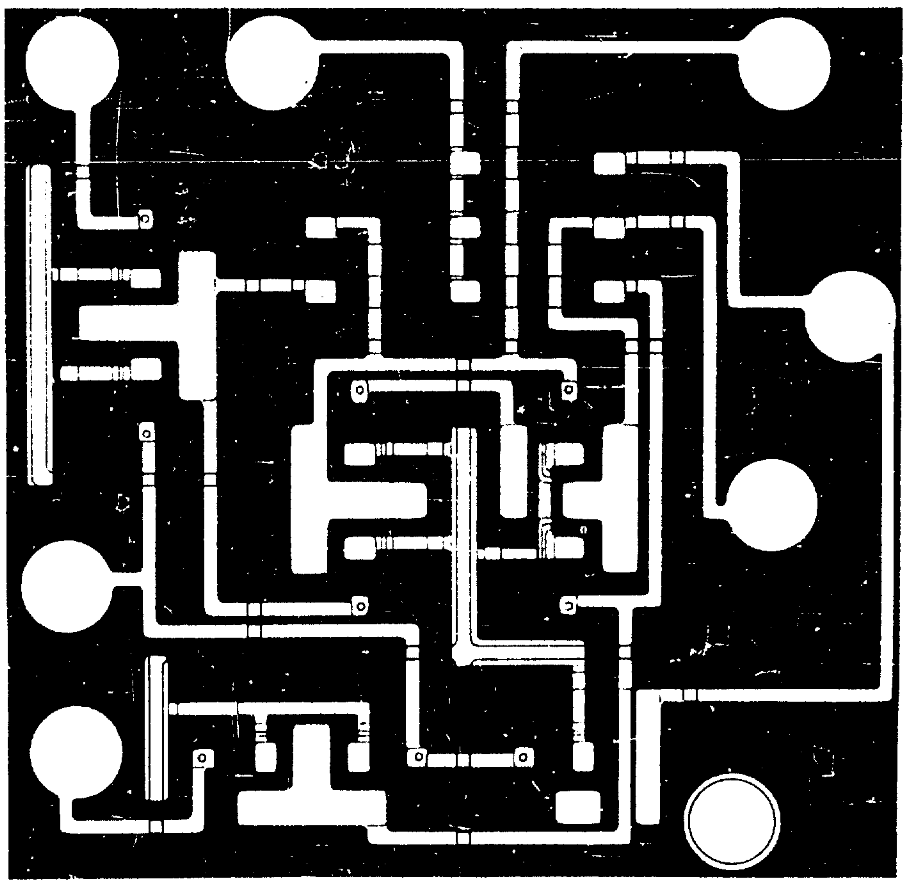


Figure 6. Metal Interconnections

to a Darlington Differential Amplifier is shown in Figures 7 through 10.*

Figure 1 depicts the thin band or "windows" which result from the process used to isolate electrically from one another the individual transistors and resistors on a silicon wafer.

By means of a chemical oxidizing process, the surfaces of the wafers are encapsulated and passivated by silicon dioxide. These wafers, which are sawed from an artificially grown crystal, are then coated with a photosensitive material in a darkroom and exposed to light through a high-resolution mask. The portions not exposed are soluble and are easily removed by a solvent rinse.

An etch is then used to dissolve the silicon dioxide from the areas not protected by the film of photosensitive material. In this manner, then, "windows" are photoengraved through the protective silicon dioxide.

In the isolation diffusion process, one step of which is illustrated in Figure 2, the silicon wafers are placed into a special high-temperature furnace where the atmosphere contains boron in a gaseous state. Through the diffusion process, this element permeates the surface of the silicon wafer only where the silicon surface of the wafer has been exposed by the photoengraving method described previously. The silicon dioxide protects the underlying silicon from the dopants even at elevated temperatures. The temperature is then raised to 1300°C; oxygen is introduced, and the boron element diffuses simultaneously from the middle. Diffusing from both sides, this impurity leaves pockets of the original N-type material. These pockets are located beneath the wafer surface areas that were protected by oxidation.

The diffusion process creates areas of P-type material which serve to isolate the areas of original N-type material from each other.

A new layer of silicon dioxide is formed by surface oxidation during the diffusion process in areas where the original silicon dioxide was etched away.

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* The photographs shown in Figures 1 through 10 have been reproduced through the courtesy of Fairchild Semiconductor, a division of Fairchild Camera and Instrument Corporation.

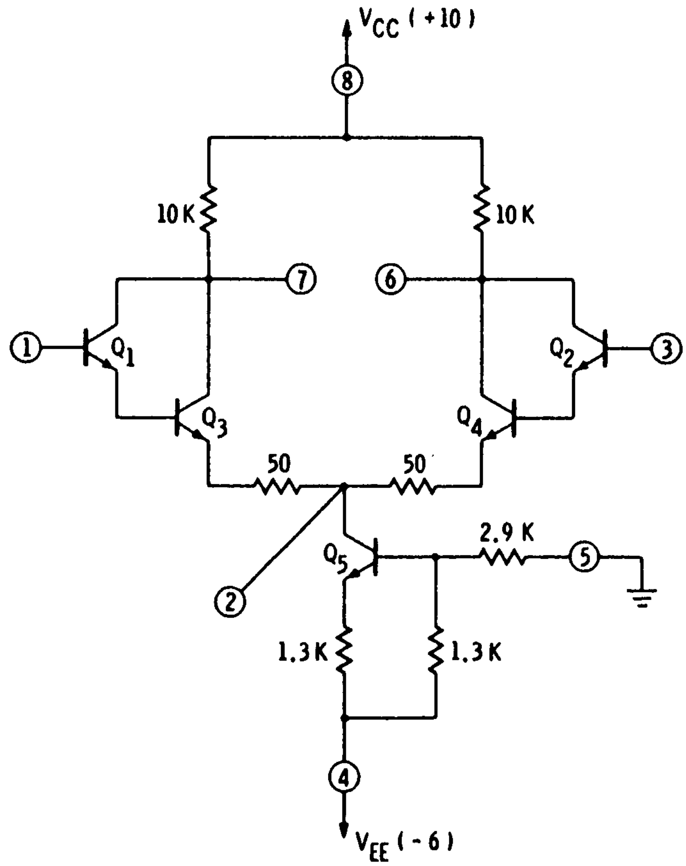

Figure 7. Schematic Diagram, Darlington Differential Amplifier

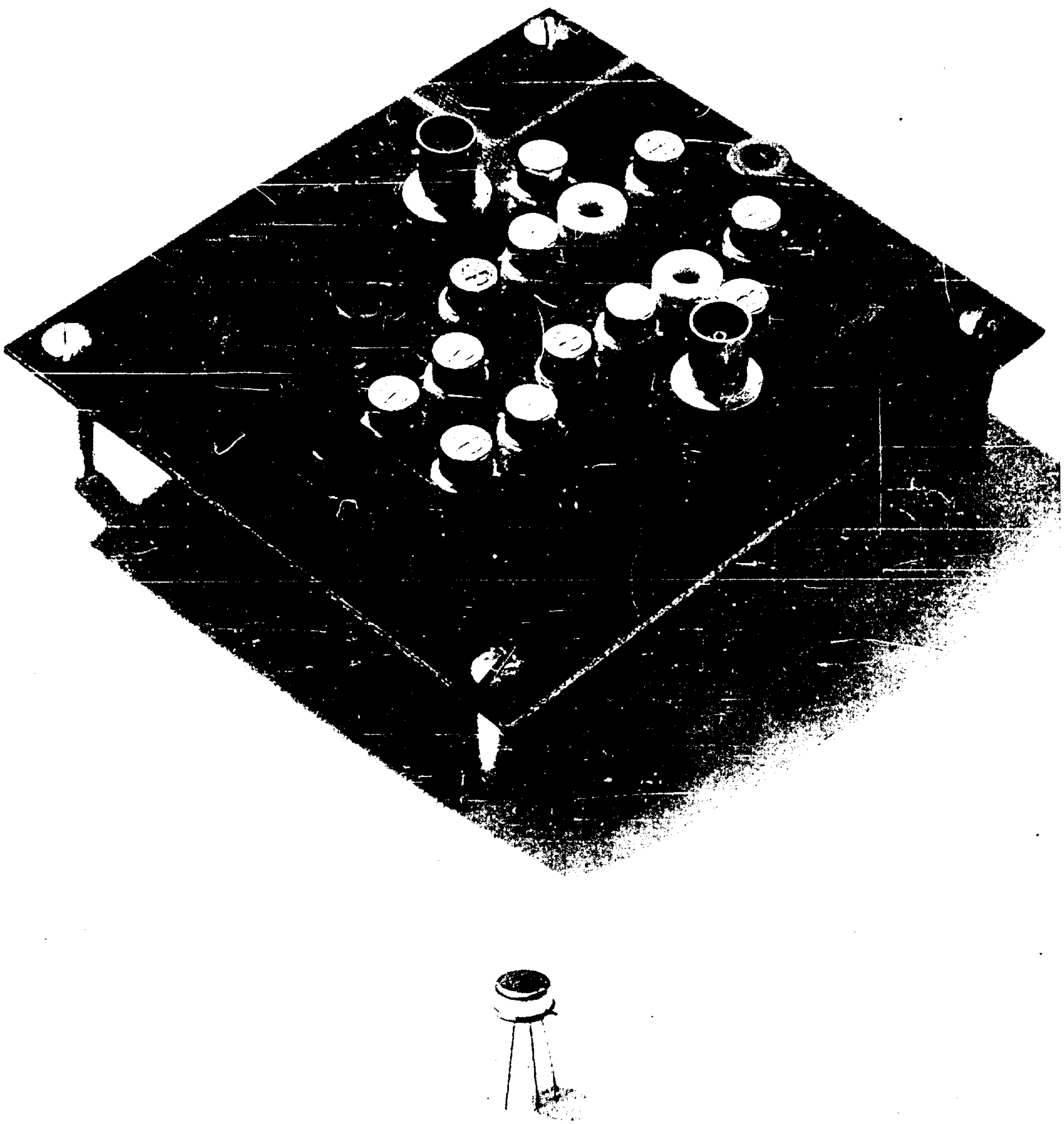

Figure 8. Breadboard Using Conventional Components

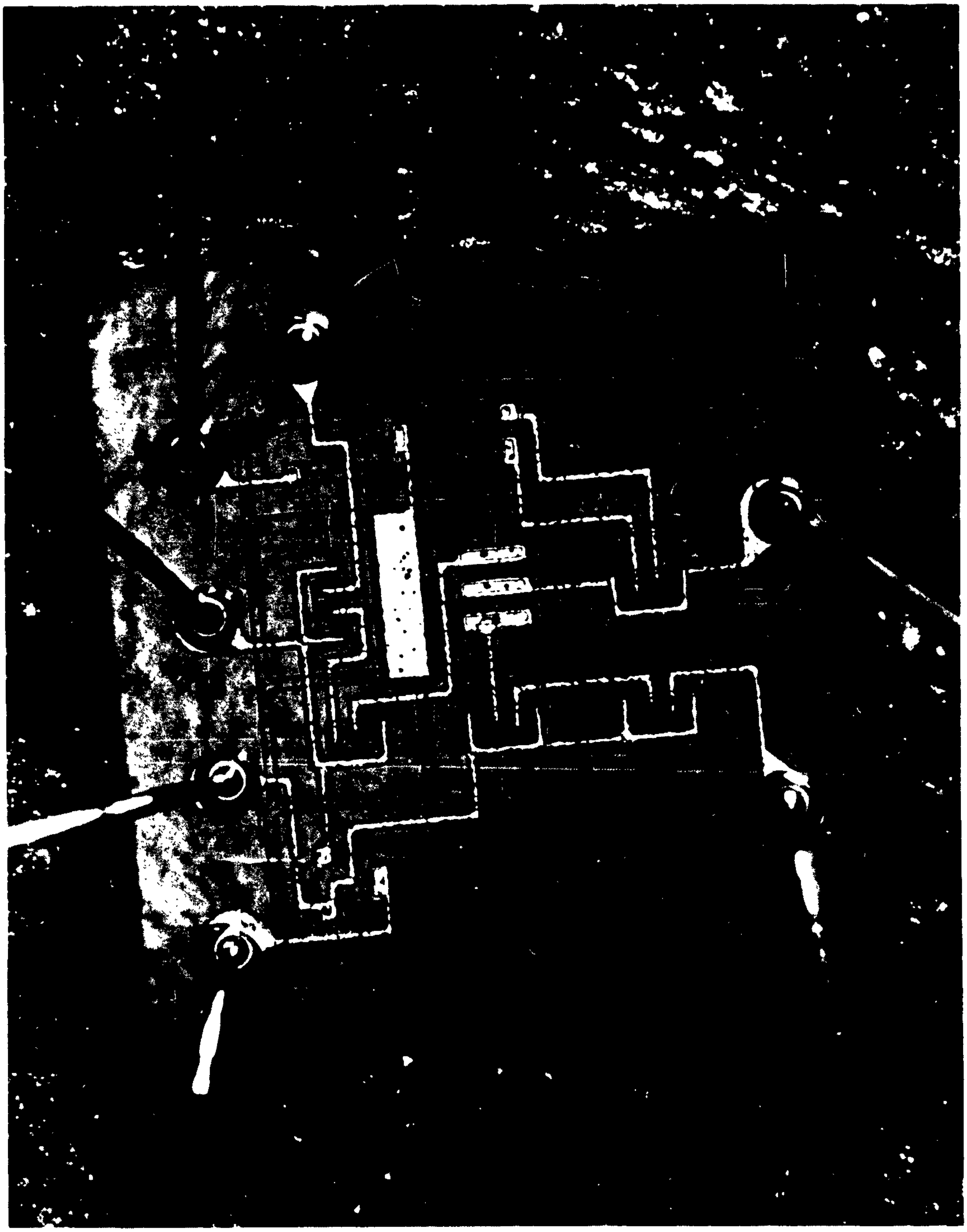

Figure 9. Finished Integrated Circuit with Lead-Out Wires

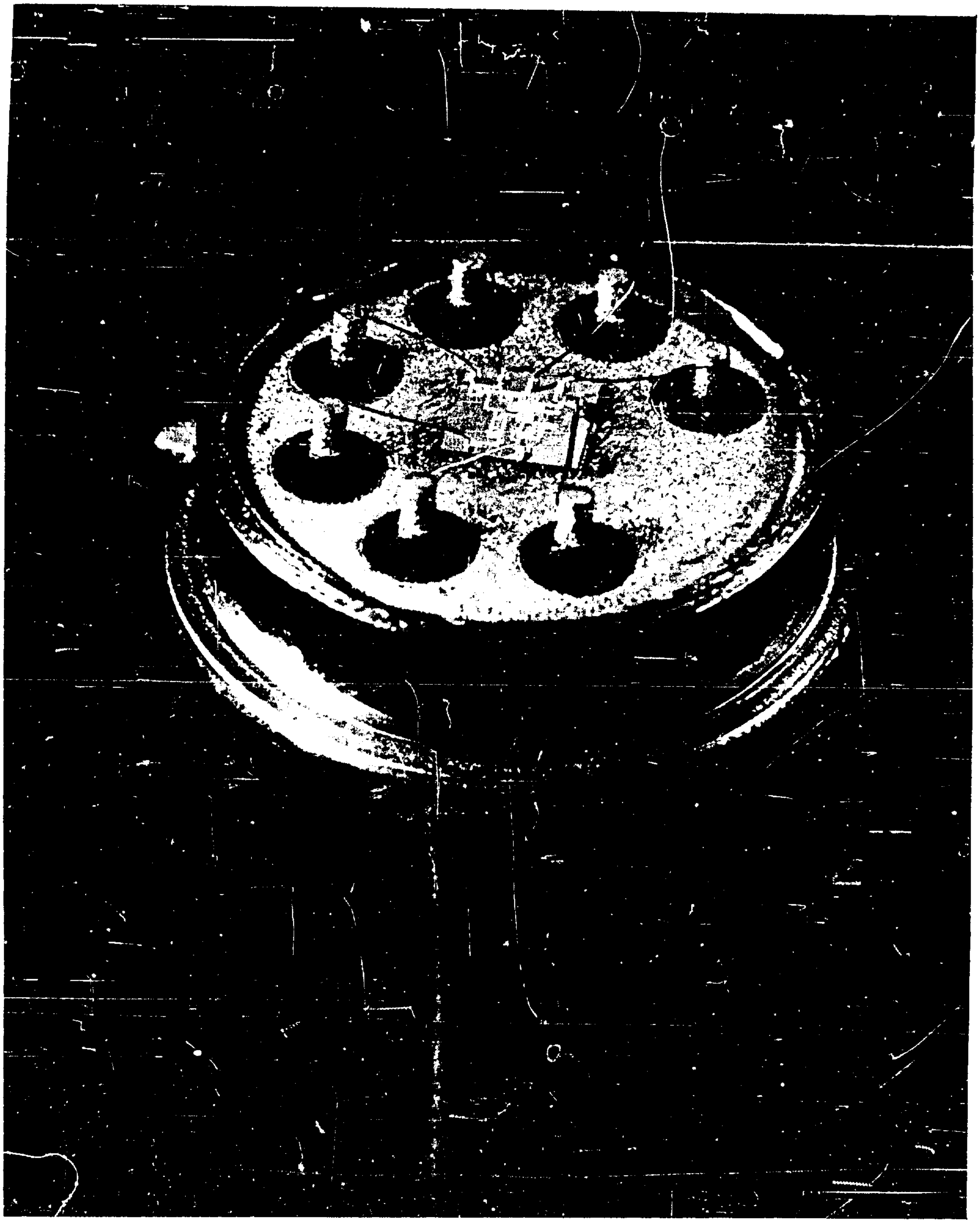

Figure 10. Wafer Mounted in a TO-5 Transistor Package

After another masking and etching process has been carried out, a second boron impurity diffusion simultaneously forms the base region of the transistors and all the resistors in the circuit (See Figure 3). As the diffusion progresses, the cut-out portions of the wafer surface are re-oxidized by the oxygen atmosphere in the furnace and sealed against contamination or injury.

As the impurity penetrates into the wafer, it proceeds laterally and diffuses into the silicon covered by the original protective dioxide. The doping level of the base of the transistor is very similar to that of standard transistors. The resistivity of the diffused area is thus a convenient value for use as the diffused resistors.

To remove oxide for the emitter diffusion and for the topside collector contacts, another precisely indexed masking step is performed (See Figure 4). Phosphorus - an n-type impurity - is deposited on the surface in another high-temperature step. At approximately 1200°C, diffusion takes place and, again, silicon dioxide forms as the diffusion progresses. This formation covers the photoengraved area and seals the surface, and side diffusion carries the junction underneath the protective layer. In each case, therefore, the diffused region ends underneath an oxide which existed previously. This oxide gives permanent protection against exposure to the outside environment to the actual junctions of the device.

Figure 5 illustrates the point at which the transistors and resistors of the circuit are completed. To connect them together into the desired logic circuit, metal interconnections are evaporated onto the surface of the silicon wafer. Before this can be done, however, a hole must be photoengraved over the appropriate regions of the devices so that the evaporated metal can make contact. A masking step similar to the others brings this about.

Metal interconnections are formed in another precise photoengraving step (See Figure 6). First the aluminum layer is masked and selectively etched to leave a pattern of interconnections between transistor and resistor elements. The wafer is now electrically complete. The only remaining steps required are for the wafers to be cut into individual circuits, and for each of the circuits to be packaged.

SECTION II

TRANSDUCERS

A transducer, in the broadest sense of the word, is a device which transforms one type of energy into another. In this report the word is used in a more restricted sense, such as, a device which transforms other forms of energy into electrical energy. In general, there are no separate transducers for pressure, temperature, etc. Instead, there are various methods of transduction and the physical parameter being measured is, within limitations, determined by the manner in which the methods are applied. Hence, a logical approach to a discussion of transducers should begin with the methods of transduction. Finally we should consider the applications to the measurement of various selected physiological parameters. Since this report deals primarily in microminiaturization, only those techniques which lend themselves to some degree of size reduction will be considered.

1. Resistance Change

Due to techniques such as thin-film deposition, molecular beam deposition, and molecular diffusion, resistors can be made extremely small in size. The resistivity of a given material is a function of temperature. By a suitable choice of material, or combination of materials, the resistivity can be made to vary linearly over a wide range of temperatures with a large resistance change per degree change in temperature. The thermistor is an example of a device which is widely used for the measurement of temperature.

If it is desired to measure any other parameters, such as pressure or force, it becomes necessary to vary the resistance mechanically. Size reduction in this case is a function of how small the mechanical portions may be manufactured.

2. Capacitance Change

Capacitors are also capable of being microminiaturized. The capacity of a capacitor of given dimensions is a function of the dielectric constant of both the material and distance between the plates. The dielectric constant

is in turn a function of the temperature and once again, by the choice of proper materials, this temperature variation can be made quite sensitive and fairly linear over a given temperature range. If the capacitor is placed in the resonant circuit of an oscillator, the frequency of the oscillator will vary with temperature. The temperature telemeter made by American Electronic Laboratories, works on this principle. (See Figure 11).

If one plate of a capacitor is made moveable, it becomes possible to use a capacitor to measure pressure, force, etc., since capacitance is also a function of the distance between the plates of the capacitor. This principle is used in the ordinary condenser microphone. In this case, one would use a dielectric whose constant varied very little with temperature.

3. Inductance Change

Although inductors cannot be microminiaturized except for very small values of inductance, their uses in transduction should be mentioned. The easiest and most convenient way to vary the inductance of an inductor is by acting upon the core material. The magnetic permeability of core materials is a function of temperature, and this fact can be used to change the frequency of an oscillator in the same manner as a capacitor. Furthermore, the position of the core material in the coil affects the inductance, and hence pressure, force, etc. can be measured by varying this positioning which in turn will vary the frequency of an oscillator.

4. Semiconductors

It is a well-known fact that transistors are temperature dependent, since the base resistance is a function of temperature. It has also been reported that the base region of a transistor is sensitive to pressure and this phenomenon has been used to pick up sound.

Mention should also be made of various electrical signals in the body which it is desirable to telemeter. The most obvious ones are EKG, EEG and EMG potentials. It is also possible to obtain electrical signals giving information on the concentration of various ions in the body. Foremost among these are hydrogen ion concentration (pH), oxygen partial pressure (pO_2), and carbon dioxide partial pressure (pCO_2). The cells most widely used for these measurements are the glass electrode, Clarke electrode, and

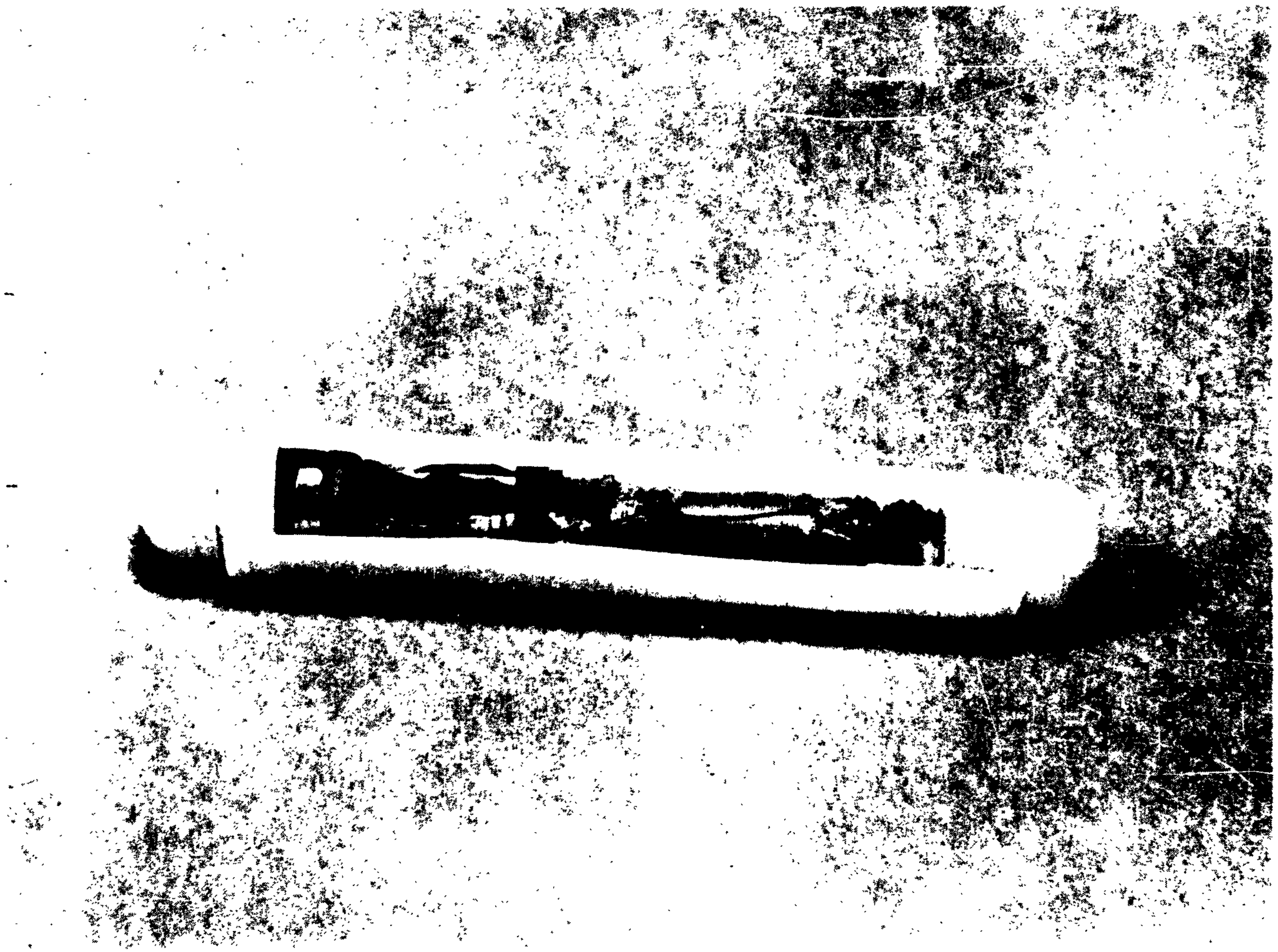

Figure 11. Temperature Telemeter

the Severinghaus electrode, respectively. These electrodes characteristically require electronic circuitry having a high input impedance, especially in the case of the glass electrode and direct coupled amplifiers, since the variations in these potentials are normally very slow. The use of d-c amplifiers may be avoided by using a voltage controlled oscillator or a blocking type of oscillator as discussed in Appendix D.

SECTION III

POWER SOURCES

Even though microminiature circuits utilize very low currents due to their semiconductor active elements, it very often becomes extremely difficult to find a power source which is comparable in size to the circuits themselves. By power sources, we mean those electrical sources which provide sufficient current to drive telemetry circuits. In general, the current requirements of a given telemeter depend upon its output power, the efficiency of its associated circuits, and its circuit complexity. The lower limits would most likely lie in the vicinity of 10 to 100 μamps for a simple oscillator having a range of several feet.

The most common power source presently used in telemetry is the electrochemical cell (battery) which transforms the energy of its chemical reaction into useful electrical energy. Some energy is lost due to side chemical reactions and thermal effects but the efficiency is still quite good.

Next in order of importance are solar cells which transform electromagnetic energy from the sun into direct electrical current. These cells fall into the more general classification of photovoltaic devices. If the junction between two semiconductors of the p- and n-type respectively, is exposed to electromagnetic waves of high frequency (generally in the optical range), a flow of current occurs in an external conductor connected between the two semiconductors. Very simply put, this phenomenon is the basis of photovoltaic and photoresistive devices.

Mechanical movement can potentially be utilized to generate electrical energy. This conversion can be accomplished by using either a type of permanent magnet generator or possibly the direct piezoelectric effect. The first method utilizes the Faraday effect, i.e., a conductor moving in a magnetic field tends to have a current induced in it. This electromotive force is proportional to the length of the conductor, the velocity of the conductor, and the magnetic field strength. The second method uses a piezoelectric material such as quartz or barium titanate. These materials

have the property that when a stress is applied to them, an electric charge is generated. This charge can then be used as a source of electrical potential.

Another source of power which is presently being widely investigated is the fuel cell. Two types are readily distinguishable: (1) those having a liquid electrolyte; and (2) those having a fused electrolyte. These two types may be further sub-divided into: (1) direct, where the electromotive force is due to the fuels fed to the cell, and, (2) indirect, where the electromotive force is generated by a pair of electrodes which are regenerated by the feed fuel. The principle of operation of the fuel cell is basically the same as that of the battery. The life of the fuel cell, in contrast to that of the battery, is indefinite and theoretically the cell should operate as long as fuel is being fed to it. Its reliability and efficiency are also theoretically equal to or superior to that of the battery.

When two dissimilar metals are joined, an electromotive force is produced. The electromotive force produced is proportional to the temperature difference, the constant of proportionality being a function of the materials used in the junction. This constant is called the thermoelectric conversion factor. The thermocouple operates on this principle. In practice, two junctions are necessary. These junctions are maintained at different temperatures. Each junction can be considered as the half cell of an electro-chemical cell. Common junctions used are iron-constantan, copper-constantan and semiconductor. By using thermocouples either in series or parallel, thermopiles can be built up which will produce higher voltages or currents.

It is possible to use radioactive decay to obtain working voltages. Devices for doing this are called nuclear cells. There are five types presently being worked on, they are: (1) <u>Slow Electron Converter</u> - uses the interaction of β-particles with matter to produce slow electrons which are then collected; (2) <u>Direct-Charging Converter</u> - collects β-particles on a conducting plate, insulated from the radioactive material, producing very high voltages; (3) <u>Contact-Potential Converter</u> - uses two

dissimilar electrodes separated by an inert gas which gives up slow electrons when it is bombarded by β-particles; (4) Semiconductor Junction Battery - uses large amount of electrons produced when β-particles bombard a semiconductor junction; and, (5) Thermocouple Type - uses increased temperature produced when matter absorbs β-particles to drive a thermocouple junction.

Various methods have been suggested for utilizing physiological sources of power by using one or another of the methods mentioned. One of the more feasible suggestions is the use of gastric pH to generate an electrochemical electromotive force. It has been shown that the pH of the stomach can provide sufficient power to activate a simple telemeter circuit, although to the author's knowledge this technique has not been reduced to practice.

A second technique which has been proposed is mechanical in nature and postulates the use of muscle action to drive a generator. The most logical method would seem to be a belt or strap around the rib cage. A very efficient generator would be required to make this technique practical.

The third technique worth mentioning employs an implanted (or at least in good thermal contact with the body) thermocouple and a second thermocouple exposed to the environment. This technique will not become practical until more efficient and compact thermopiles are available.

At present the smallest and most reliable source of power for biotelemeters is batteries. The characteristics of the most commonly used types are given below.

BATTERIES

Dry Cell - These cells utilize a carbon anode and a zinc cathode with a paste electrolyte. They are by far the cheapest and have a high power per dollar ratio. Availability is also extremely good, as is the range of values, since it is common to connect the 1.5 volt cell in series, parallel, or series-parallel to obtain various values in off-the-shelf items.

Mercury Cells - These cells utilize a mercuric oxide anode, a finely divided zinc cathode, and potassium hydroxide electrolyte. The advantages

are: (1) high ratio of energy per unit volume and weight; (2) long shelf-life; (3) no need for recovery periods during discharge; and, (4) fairly constant potential during discharge. They operate within a fairly wide temperature range up to 130° F but do not operate well at low temperatures. The standard voltage per cell is either 1.35 or 1.40 volts.

Nickel-Cadmium Cells - These cells use nickel and cadmium electrodes and are rechargeable.

Their advantages are: (1) rechargeability; (2) fairly constant potential during discharge; (3) good charge retention; (4) operate well at low temperatures; (5) rugged construction; (6) addition of electrolyte is not required; (7) no corrosive fumes; and, (8) low cost per hour use. The normal output is 1.25 volts.

Silver-Oxide-Zinc Cells - These cells utilize a zinc anode, a silver oxide cathode, and an electrolyte of potassium hydroxide. The nominal cell voltage is 1.5 volts and the batteries have an excellent shelf life.

Table B-I, Appendix B, gives a list of representative batteries of the types discussed. The smallest size cells of each type were chosen, since our emphasis in this report is on miniaturization.

Techniques have been reported in the literature* where power is derived from an external source. The transmitter derives its operating power from the energy of an externally generated electromagnetic field. Such techniques are very valuable, since, in many instances, the micro-miniaturized telemeter is smaller than the battery required for operation. Thus, a saving of 30-50% in overall size can be achieved by eliminating the battery. The circuits used in these techniques are discussed in Appendix B.

*See power supply references, numbers 4 and 5.

SECTION IV

APPLICATIONS OF MICROMINIATURIZED TELEMETERS TO BIOLOGICAL PROBLEMS

Certain specific problems in biological telemetry present themselves with such frequency that it would be advantageous to review their status with respect to microminiaturization. The specific problems involve the telemetry of physiological parameters, environmental parameters, or geographic position. With respect to geographic position, a radio signal generator carried by the animal in question, used in conjunction with directional receiving antennas is adequate.

If it is desired to transmit information concerning physiological or environmental parameters, then the appropriate transducer must be available. This transducer may be an integral part of the electronic circuitry such as a capacitance, inductance, or resistance, or it may be considered as an external component. From the viewpoint of microminiaturization, the former case is most desirable since a component which is necessary for the proper operation of the circuit also provides the desired information. Aside from the transducer considerations, the following telemeter specifications are of utmost importance in any particular application:

1. Weight of transmitter including power source.
2. Overall size of transmitter.
3. Range of transmitter.
4. Expected lifetime of transmitter.
5. Length of antenna.

All of these factors are inseparably linked together and compromises are unavoidable. We wish to minimize size, weight, and antenna length, while at the same time maximizing the transmitter's range and the expected lifetime. The inter-relationship between these design objectives is illustrated in the following example. If we attempt to increase the telemeter's range of operation, we know that we must transmit more power. This increase requires a larger current drain from the power source which

in turn means that the expected lifetime of the transmitter will be decreased unless the battery is made larger. However, an increase in battery size results in a total increase in the size and weight of the transmitter. This then violates one of our design objectives. If the telemeter had been originally designed using conventional components, such as cased transistors, etc., the circuit designer would have then been able to obtain his increased range, without increasing size and weight, by employing microminiaturization techniques.

From this simple chain of reasoning, it is obvious that microminiaturization can be used to aid the biologist in obtaining data which heretofore had been denied him. Due to the decreased size and weight of the transmitter package, he may gain access to regions of the animal's body which were previously inaccessible for long term measurements. Also, he is able to employ biotelemetry in animals which were previously thought to be too small to bear the burden of a transmitter package.

As a further example, let us consider a dental transmitter for pressure measurement. Such a transmitter package could be made the size of an average tooth provided the experiment was conducted in the laboratory and at short ranges. It could probably be one-half this size if the experiment were limited to several hours. By using one of the "echo" techniques described in Appendix B, the transmitter could be envisioned as small enough to fit in a large cavity. In this instance, it must be mentioned that the coil and transducer used would actually set the limit on the amount of size reduction possible. However, as was previously mentioned, the microminiaturization of coils lags behind that of resistors, capacitors, etc.

Through microminiaturization of components, the biologist who is interested in tracking animals, can increase his battery size, and hence range, without sacrificing the size of his existing telemetering package. However, the range of a transmitter may be further limited by factors other than total radiated power and receiver sensitivity. Some of these factors are described and discussed in Appendix C. If the biologist is limited by one of these factors, he can take advantage of the increased battery size

to prolong the duration of an experiment. This could conceivably permit the observation of parameters whose variation is expected to be very slow, lasting hours, days, or even months. A case in point would be the monitoring of the body temperature of hibernating animals. The excellent reliability of microminiaturized circuits must also be remembered.

The increased space made available in a given telemeter by microminiaturization facilitates inclusion of additional circuits in the package. Therefore, several parameters could conceivably be measured in the amount of space previously required for the measurement of a single parameter. Thus, a transmitter originally designed to transmit a single frequency to track a pigeon in flight could also be modulated to transmit such parameters as EGK, EEG, surface temperature, etc.

Bearing the preceding explanations in mind, we will now return to a consideration of practical telemetry situations.

The animal is considered to have a radio transmitter attached externally or internally on his body. The receiver for the animal transmitter is located on or above the ground's surface. In the latter case, it may be on a tower, attached to a balloon, or in an airplane. It must be appreciated that there are so many possible circumstances that no exact figures may be offered with respect to the factors of size, weight, duration of transmission, range of transmission, or antenna length unless a specific application is envisioned. We must therefore draw upon the previous experience of engineers employed in the area of building biological telemeters. The following description represents an educated estimate of what might be possible to build by applying state-of-the-art microminiaturization in the very general case of an unmodulated transmitter.

The smallest line-of-sight transmitter producing a signal which could be received under ideal biotelemetry conditions would be a cylinder, having the approximate dimensions of 4 mm in diameter and 4 mm in height. This size is considered sufficient to encompass a number of circuits and would be adequate for all the electronics which might conceivably be desired for the usual telemetry problems. In addition, a miniature battery source would be a cylinder about 8 mm in diameter and 12 mm in height, (three cells approximately the same size as the Hg 312 given in Table I, Appendix B

are used here. Such a device would weigh on the order of 30 grams. Assuming continuous transmission, this device would transmit for about 12 hours. Utilizing intermittent transmission, the duration of operation could be extended several-fold. The power radiated would be adequate to transmit line-of-sight at the earth's surface for ranges calculated to be up to 10 miles with a very sensitive receiver and very directional antenna. The length of the transmitting antenna is a function of the frequency of operation of the transmitter. However, the considered advantageous frequency of operation is in the area of 100 mc. At this frequency a quarter-wave length antenna is about 75 cms. long.

In order to achieve transmission past the curvature of the earth, several circumstances may apply. One case is that of reflection from the ionosphere. Another case is actual curvature of the radio signal due to refraction in the upper layers of the atmosphere. In the latter case, it would be necessary to utilize wavelengths for which the microminiaturization state-of-the-art would not be very effective. Since large coils are necessary, the transmitter would be taken out of the realm of microminiaturization.

In the first case, as stated in Appendix C, frequencies on the order of 3.5 to 7 mc and the previous specifications for line-of-sight transmitters, may also be applied to transmission by reflection from the ionosphere. However, the antenna length becomes appreciably longer. Thus, at 5 mc, the quarter-wave length antenna is 15 meters. Such an antenna length would probably be unacceptable except possibly in the case of certain large migratory birds over long distances of water. The reflection phenomena are observed for shorter wave lengths as well as the longer ones, although far less frequently at the shorter wavelengths. If the experimenter desires to work at the higher frequencies, and is willing to accept the reduced probability of signal acquisition, the length of a quarter-wave length antenna at 50 mc, for example, would be 1.5 meters.

The last type of transmission to be considered is that of magnetic coupling. This type of transmission may be used for laboratory telemetry applications or in a situation in which the animal is separated from the

receiver by short distances of some sort of poorly propagating media. The circumstance considered here is that of burrowing animals, where, for example, there is a quantity of earth between the animal and the observer. Under these circumstances, the radio signal would be attenuated past recognition. However, electromagnetic coupling can be used with fairly satisfactory results. The usefulness of this type of transmission is due to the fact that the effect of the earth on radio waves is not the same as its effect on the magnetic lines of force. Although it is impossible to predict with great precision what the range would be, since it depends to a large extent on the medium involved, there are certain tentative conclusions which have been reached by engineers working in this area.

Considering transmitters which have small battery supplies capable of being carried by burrowing animals the size of rabbits, the range due to coupling through earth or through similar conducting media is on the order of a few feet at best. However, depending upon the nature of the experiment, this range may be satisfactory to some investigators. The frequency of operation of such transmitters can extend anywhere from 60 kc to 2 megacycles. Their size and weight is a function of the frequency of operation. As an example, a transmitter operating in the range of 200 kc and supplied by small mercury batteries approximately 8 mm in diameter and 4 mm in thickness, with the transmitter package occupying about 10 mm in length by 5 mm in diameter, can transmit about six feet. There is no antenna required with these devices since there is no actual radiation and the coil of the oscillator provides the magnetic field required for coupling.

A second transmitter operating in the range of 2 mc can be made even smaller, about 10 mm in length and 3 mm in diameter. A battery size for this transmitter is of the same magnitude as the previous one. The range of transmission is several feet. The duration of transmission that has been achieved is on the order of several months. Again, no antenna is required because the transmitter is electromagnetically coupled to the receiving antenna. All of these projections assume a maximally efficient receiving coil coupled to a maximally efficient receiver.

In a laboratory environment, such a transmitter, made capable of being modulated, could be implanted and used very effectively to measure temperature, pH, pressure, etc. In the laboratory it also becomes feasible to use an external power source such as those mentioned previously, and thus, an approximate 50% size reduction could be realized by the elimination of the battery. The life of the unit would also be greatly extended.

The question arises pertaining to the potential uses of microminiaturized telemeters in the future. The two greatest advantages of microminiaturization are the small sizes attainable and the increase in the number of circuits available to perform several measurements in a given space. These advantages are very appealing from the biologist's point of view, in the case of implanted short range telemeters, and also in the case of longer range externally supported telemeters. In the field of implanted telemeters, it is possible to visualize a telemeter which could be implanted in the thoracic cavity to continuously transmit cardiac potentials, and also apply electrical stimulation upon command. An externally attached telemeter which would transmit EKG's and provide for lead switching upon command also seems possible, even for some of the smaller animals.

An entire realm of telemeters, both implanted and externally attached, capable of supplying electrical stimuli upon command and transmitting the resulting response, can now be envisioned due to the application of microelectronic techniques which are entirely within the state-of-the-art.

SECTION V
CONCLUSIONS AND SUMMARY

This Technical Report has presented, in a semi-technical manner, a brief description of microminiaturization techniques and their potential applications in biological telemetry.

Microminiaturization techniques are generally applied to circuits and not to single components. The equipment for the application of these techniques is not generally available to the biologist, therefore, he must rely on the electronics industry to provide the circuits which he requires. Appendix A includes a list of companies and organizations actively engaged in microminiaturization from whom additional information may be obtained.

At present, the cost of microminiaturization is very high on a single circuit basis, but may be reduced when larger quantities are desired. The largest amount of design has been accomplished on circuits used in electronic computers. Very little design has been resolved on circuits which are useful in the telemetry applications discussed herein. However, it presently appears that the biological telemetry applications may be more feasibly developed by the utilization of the solid circuit technique. Circuits most commonly used in biotelemetry must be further evaluated and those circuits found to be most versatile should be microminiaturized on an individual scale. Once a satisfactory technique is resolved, many additional applications will be suggested by continued utilization and research.

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APPENDIX A

APPENDIX A

TABLE A-I

Designation	Type of Device	Height (Max.) (in.)	Width or (Max.) Diameter (in.)	Classification
81	Vacuum Tube	6-1/4	2-7/16	Half-Wave Rectifier
80	Vacuum Tube	4-11/16	1-13/16	Full-Wave Rectifier
78	Vacuum Tube	4-15/32	1-9/16	Pentode
35W4	Miniature Vacuum Tube	2-5/8	3/4	Half-Wave Rectifier
6AG5	Miniature Vacuum Tube	2-1/8	3/4	Pentode
1AC5	Miniature Vacuum Tube	1-3/4	.400	Pentode
CK5784WB	Subminiature Tube	1-1/2	.400	Pentode
CK6021	Subminiature Tube	1.375	.400	Double Triode
2N1056	Transistor	.240	.460	Switching
2N404	Transistor	.235	.310	High Frequency Switching

TABLE A-II

This table presents a listing of companies engaged in miniaturization from which additional information may be obtained by those readers interested in microelectronics. Also, this listing illustrates the number of companies involved in miniaturization.

I. Reduction of Conventional Components

1. A.C. Spark Plug, Division of General Motors Corp.
2. Airborne Instruments
3. American Bosch Arma Corporation
4. Autonetics
5. Bendix Corporation
6. Burroughs Research Center
7. Cleveland Metal Specialties Company
8. Diamond Ordnance Fuze Laboratories
9. Electronic Engineering Company
10. Engineering Electronics Company
11. Francis Associates
12. General Electric Company
13. Hughes Aircraft Company
14. IBM
15. Keystone Carbon Company
16. King Electronics
17. Massachusetts Institute of Technology Instrumentation Labs.
18. P.R. Mallory and Company, Inc.
19. Radio Corporation of America
20. Raytheon Company
21. Republic Aviation
22. Signal Corps
23. Sippican Company
24. Sylvania Electric Company
25. Walkrit Company

II. Two-Dimensional Approach

1. Aerovox Corporation
2. American Bosch Arma
3. Bell Telephone Laboratories
4. CBS Electronics
5. Centralab Division of Globe Union, Inc.
6. Denver Research Institute
7. Diamond Ordnance Fuze Laboratories
8. Fairchild Semiconductor, Inc.
9. Haloid Xerox, Inc.
10. Hamilton Standard, Division of United Aircraft Corp.
11. IBM
12. International Resistance Company
13. Lockheed Aircraft Company
14. Melpar, Inc.
15. Motorola, Inc.
16. National Bureau of Standards
17. Philco, Inc.
18. Servomechanisms, Inc.
19. Sprague Electric Company
20. Sylvania Electric Products, Inc.
21. Tear, Inc.
22. Varo Manufacturing Company
23. Westinghouse Electric Corporation

III. Solid Circuit Approach

1. Bell Telephone Laboratories
2. Diamond Ordnance Fuze Laboratories
3. Fairchild Semiconductor Corporation
4. IBM
5. Merck, Sharp and Dohme
6. Radio Corporation of America
7. Raytheon Company

8. Sperry Rand Corporation
9. Texas Instruments, Inc.

IV. Molecular Electronics

1. Westinghouse Electric Corporation

APPENDIX B

APPENDIX B

TABLE B-I

This table lists the size and operating lifetime of various types of batteries made by representative manufacturers. This table is by no means to be considered complete, but only representative. The figures presented for the number of cells and operating power refer to a transmitter drawing three milliamperes and having a cut-off voltage of 3.0 volts.

The following companies will provide literature upon request:

1. Gulton Industries, Inc.
   Alkaline Battery Division
   212 Durham Avenue
   Metuchen, New Jersey

2. Sonotone Corporation
   Battery Division
   Elmsford, New York

3. Burgess Battery Company
   Freeport, Illinois

4. Union Carbide Consumer Products Co.
   270 Park Avenue
   New York 17, New York

Manu. Design	Type	Manufacturer	Dimensions (in.) L (or D)	W	T (or H)	# Cells Required	# Hrs.
375 E	Silver Oxide Zinc	Union Carbide	.450	-	.200	3	-
S40E	Silver Oxide Zinc	Union Carbide	.450	-	.155	-	-
S13E	Silver Oxide	Union Carbide	.310	-	.20	3	20
Y Cell	Dry Cell	Burgess Battery Company	.562	.562	.125	3	19
Hg 312	Mercury	Burgess Battery Company	.310	-	.140	3	12.5
CD 1	Nickel Cadmium	Burgess Battery Company	.460	-	.225	3	5
YT Cell	Dry Cell	Burgess Battery Company	.562	.562	.256	3	54
S116	Nickel Cadmium	Sonotone	.560	-	.615	-	-
2VO.080	Nickel Cadmium	Gulton Industries, Inc.	.960	-	.670	2	-

APPENDIX B
(continued)

POWER FROM EXTERNAL R-F SOURCES

Several methods have been suggested to eliminate internal power supplies from telemeters designed for implanted use. These methods may be sub-divided into two main types: (1) passive - using resonant circuits but no active elements, and (2) active - employing active elements such as transistors.

The first method may use either a low Q or a high Q-tuned circuit, which is pulsed by an external radio frequency source. A receiver is then utilized to read the frequency of the "ring" created by this pulse. In this manner, the resonant frequency is determined. Any change in either inductance or capacitance is reflected as a shift in resonant frequency.

The second technique uses an oscillator circuit such as shown below.

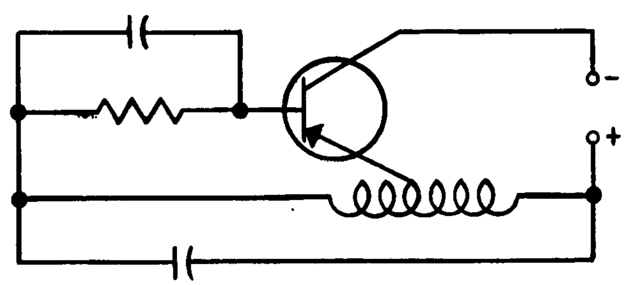

Figure B-1

Power can be supplied to this circuit by using a tuned r-f pickup and a rectifier as in Figure B-2. The radio frequency energy from an external radio transmitter is received by the tuned circuit composed of the coil A and the capacitor C_1. This radio frequency energy is half wave rectified by the diode D and filtered by the capacitor C. The resulting DC voltage is applied to the transistor between the collector and the emitter enabling it to oscillate.

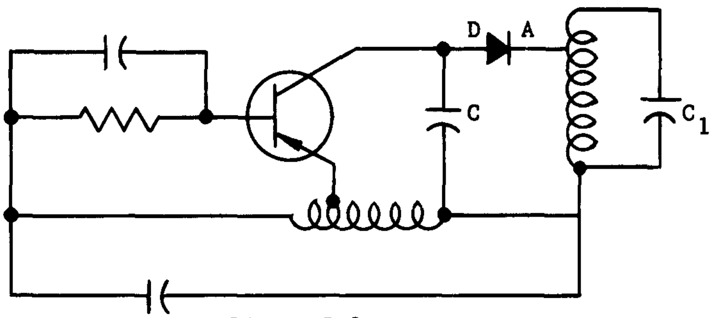

Figure B-2

One disadvantage of this arrangement is the additional size required by the inductor and filter capacitor C. By using higher frequencies, it is possible to use smaller components, but the upper limit on frequency is also set by the depth of tissue which lies between the telemeter and the external power source antenna, and by the power required by the telemeter. A frequency of 2 megacycles may arbitrarily be chosen as an upper limit.

A variation of the above technique which works on the echo principle has been described recently in the literature. The circuit is illustrated in Figure B-3. (See Power Supplies references 4 and 5.)

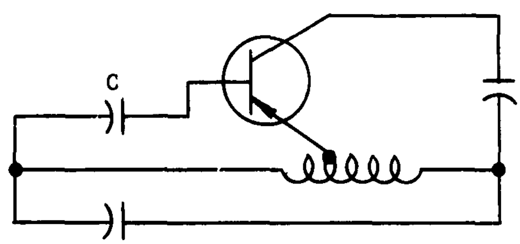

Figure B-3

Rf energy is received by the coil and current flows in the base-emitter circuit of the transistor causing the capacitor in that circuit to become charged. When the external rf energy is removed, the oscillator circuit resonates at a frequency determined by the tuned circuit. The time between the removal of the energizing rf and the beginning of the oscillation is determined by the time constant of the base-emitter circuit. Any variation of the resistance or capacitance in this circuit can thus be measured. These capsules have been used successfully to record pH and temperature. The pH recordings were obtained by placing a low impedance electrode across the capacitor C.

APPENDIX C

APPENDIX C

TYPES OF TRANSMISSION

Line-of-Sight

Line-of-sight transmission is transmission in a straight line. This refers to atmospheric transmission rather than water or earth transmission. It also may be considered as transmission up to but not beyond the horizon and should be differentiated from transmission beyond the horizon.

Curvilinear Transmission

This type of transmission is used for ranges beyond line-of-sight and does not consider the curvature of the earth as an obstacle. Thus, transmission beyond the horizon is, in one fashion or another, the capability to transmit beyond the horizon and no longer takes place in a straight line but rather in a curve beyond the obstruction of the earth's curvature. The transmission itself may, however, be in a straight line with reflections occurring from the various layers of the atmosphere, or an actual curving may occur due to the variation of the index of refraction of the ionosphere with altitude. At the present state-of-the-art, it is believed that transmission by reflection from the upper layers of the ionosphere occurs at frequencies below 60 mc and then only under the optimum circumstances. Usually, reflection occurs at frequencies below 10 mc. The considered optimum frequency range would be between 3.5 and 7 mc.

Electro-Magnetic Coupling

This refers to short-distance transmission (on the order of feet), with coupling occurring through atmosphere, water, or earth. This type of transmission is by electro-magnetic coupling (transformer) rather than by electromagnetic radiation (radio).

APPENDIX D

TELEMETRY TECHNIQUES AND PRACTICAL TELEMETERS

This appendix discusses the general bio-telemetry practices in most common use and the application of micro-circuitry in implementing them. A frequency-modulated telemeter in its simplest form consists of a tuned oscillator as shown in Figure D-1. The resonant circuit of this oscillator consists of an inductor (L) and a capacitor (C), and the frequency of oscillation is given by:

$$f = \frac{1}{2\pi\sqrt{LC}} \qquad \text{(D-1)}$$

This equation yields a good deal of valuable information. Assume that we now desire to transmit data by varying the frequency of oscillation. From Equation (D-1) we see that this can be accomplished in two ways, by varying either L or C. If C is the quantity to be varied, say as a function of temperature, then $T + \Delta T$ corresponds to $C + \Delta C$. This change in capacitance, ΔC, causes a corresponding increase or decrease in frequency, depending upon whether $\frac{\Delta C}{\Delta T}$ is negative or positive. If the transmitter is coupled to a frequency-sensitive receiver, this change in frequency can be directly related to a change in temperature. Any physical parameter which can change the value of a capacitor or inductor in a predictable fashion can be telemetered. Figure 6 illustrates an operational telemeter using this principle.

The power radiated by the coil in the tuned circuit depends upon the energy supplied. There are two ways in which one may gain access to the information supplied by the coil. At distances relatively large compared to the wavelength (5 λ), one must rely entirely on the radiated energy, while at close distances one can inductively couple into the coil. The latter action is identical to the action of a transformer with the transmitter coil as a primary coil, and the receiver coil as a secondary, as noted in Appendix C.

In the pulse modulation technique, which is also widely used, an oscillator is again used and the Equation (D-1) applies. A schematic for this type of transmitter is shown in Figure D-2. However, in this case,

the frequency of oscillation is held constant by using stable components in the tank circuit. In certain cases, a coil is used which has no tuning capacitor. By using a capacitor and a resistor, power is supplied to the transistor in pulses. The effect of pulsing a coil is the production of a large band of frequencies, each having a different amplitude. The duration of the pulse applied to the coil is determined by the time constant (T = RC) of the resistor-capacitor network. If a tuned circuit is used, energy will be radiated at a single frequency.

Once again information is obtained by changing either R or C. This in turn changes the duration of the output pulse. Decoding the output pulse duration yields the desired information.

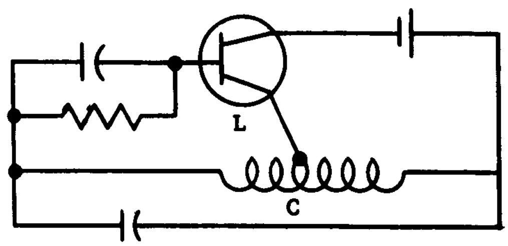

Figure D-1

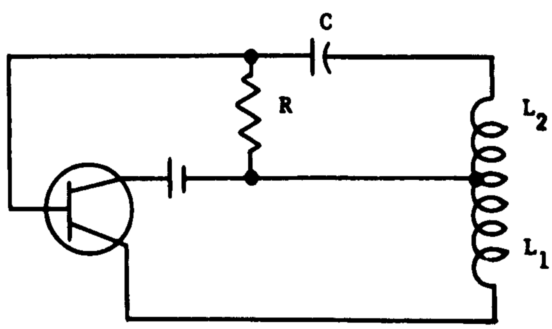

Figure D-2